Method and Apparatus for Reducing Errors due to Line Asymmetry in Devices Utilizing Coherent Population Trapping

Background of the Invention

To simplify the following discussion, the present invention will first be explained in terms of a frequency standard.

One class of frequency standards utilizes Coherent-Population-Trapping (CPT) in quantum absorbers. CPT-based frequency standards are described in US patents 6,363,091 and 6,201,821, which are hereby incorporated by reference. Since such frequency standards are known to the art, they will not be described in detail here. For the purposes of the present discussion, it is sufficient to note that in such standards, the output of an electromagnetic source that has two frequency components with respective frequencies $\nu_L + \frac{1}{2}\mu$ and $\nu_L - \frac{1}{2}\mu$ (CPT-generating frequency components), and possibly other additional components, is applied to a quantum absorber. Here, ν_L is the average frequency of the CPT-generating components. The average vacuum wavelength of the electromagnetic source is approximately c/ν_L, where c is the speed of light in a vacuum. The quantum absorber has two low energy states (which shall be referred to as state A and state B), and n high energy states, each of which can be reached by a transition from state A and by a transition from state B. Denote the high energy states by C_k, for $1 \leq k \leq n$. Additionally, the quantum absorber may have any number of other low energy states and high energy states. The mean energy of state B, E_B is taken to be greater than or equal to the mean energy of state A, E_A. Denote the frequency difference between state B and state A by $\mu_0=(E_B-E_A)/h$, where h is Planck's constant.

When the quantities μ and μ_0 are approximately equal, the quantum absorber can exhibit the phenomenon called Coherent-Population-Trapping (CPT), assuming that the value of ν_L falls in the necessary range so that the CPT-generating frequency component with frequency $\nu_L + \frac{1}{2}\mu$ induces transitions between the state A and the states C_k, and the CPT-generating frequency component with frequency $\nu_L - \frac{1}{2}\mu$ induces transitions between the state B and the states C_k. In this situation, the absorption (and fluorescence) of the CPT-

generating components by the quantum absorber is smaller than it otherwise would be, and the transmission of the CPT-generating components through the quantum absorber is greater than it otherwise would be. When μ and μ_0 are exactly equal, for fixed ν_L, the quantum absorber exhibits an absorption (and fluorescence) minimum, and a transmission maximum, of the CPT-generating components. One class of frequency standards utilizes the CPT phenomenon to adjust a frequency source such that its output frequency is equal to some function of μ_0 by maintaining the frequency μ at the value that maximizes the transmission (or minimizes fluorescence) of the quantum absorber. If μ_0 remains constant, then the frequency source can be used as a frequency standard having high accuracy, as long as a reliable method exists for determining μ_0.

Therefore, reliably accurate frequency standards based on CPT must keep μ_0 constant, and they must reliably determine the value of μ that maximizes the transmission through the absorber. To accomplish the first task, each source that causes μ_0 to vary must be carefully controlled, or else means must be applied to the quantum absorber to reduce the sensitivity of μ_0 to that source. For example, if the quantum absorber is ^{87}Rb vapor in a cell with a buffer gas and a magnetic field, then some of the sources that cause μ_0 to vary are fluctuations in the strength of the applied magnetic field, and the buffer gas pressure. Hence, reliable operation of the standard must ensure the constancy of the magnetic field and the buffer gas pressure.

For the purposes of the present discussion, it will be assumed that the standard measures the transmission through the quantum absorber. Similar arguments apply to standards that measure fluorescence, microwave emission, or some other parameter. In general, the transmitted power, $T(\nu_L, \mu)$, will be a function of both ν_L and μ. Prior art methods determine the value of μ that maximizes the transmission by utilizing an algorithm that assumes that the transmission curve is a symmetric function of μ about μ_0 for fixed ν_L when μ is near to μ_0. If the transmission curve does not satisfy this symmetry condition, the determination of μ_0 will be in error.

In quantum absorbers that exhibit the CPT phenomenon, $T(\nu_L,\mu)$ is often not a symmetric function of μ about μ_0 for fixed ν_L. Denote the Rabi frequency associated with the transition between state A and state C_k by ω_{Ak} and the Rabi frequency associated with the

transition between state B and state C_k by ω_{Bk}. Then the transmission curve $T(\nu_L, \mu)$, with ν_L held fixed, is a symmetric function of μ about μ_0 only when, for each high energy state C_k, $|\omega_{Ak}|^2 = |\omega_{Bk}|^2$. When this relation between ω_{Ak} and ω_{Bk} does not hold for each of the high energy states C_k, then $T(\nu_L, \mu)$, for ν_L held fixed, will not normally be a symmetric function of μ about μ_0, and an error will be made in the determination of the value of μ that maximizes the transmission through the quantum absorber.

Summary of the Invention

The present invention is an apparatus and method for measuring CPT. The apparatus includes a quantum absorber that is irradiated by radiation from an electromagnetic radiation source. The quantum absorber includes a material having first and second low energy states coupled to a common high energy state. Transitions between the first low energy state and the common high energy state or between the second low energy state are induced by electromagnetic radiation. The electromagnetic radiation source generates electromagnetic radiation having first and second CPT-generating frequency components. The first CPT-generating frequency component has a frequency ν_L-ν, and a first CPT component amplitude. The second CPT generating frequency component has a frequency ν_L+ν and a second CPT component amplitude. The apparatus also includes a detector for generating a detector signal related to the power of electromagnetic radiation that leaves the quantum absorber. The detector signal exhibits an asymmetry as a function of frequency in a frequency range about a frequency ν_0. The apparatus includes a CPT servo loop that alters ν in response to the detector signal and an asymmetry servo loop that alters one of ν_L, the first CPT component amplitude, and the second CPT component amplitude in a manner that reduces the asymmetry.

In one embodiment, the apparatus includes an EM (ElectroMagnetic) frequency control circuit that determines ν_L. The EM control circuit is responsive to an EM frequency control signal. In this embodiment, the asymmetry servo loop alters the EM frequency control signal. In another embodiment, the asymmetry servo loop alters one or both of the first CPT component amplitude and the second CPT component amplitude. In one embodiment, the electromagnetic radiation source further generates additional frequency

components for altering an AC Stark shift in the quantum absorber, the additional frequency components having amplitudes that are determined by an AC Stark shift control signal. This embodiment includes an AC Stark shift servo loop that generates the Stark shift control signal. In one embodiment, the electromagnetic radiation source includes a source for generating electromagnetic radiation having a frequency ν_L in response to a first control signal and a modulator for modulating the generated electromagnetic radiation at a frequency ν in response to a second control signal. In one embodiment, the EM radiation source includes a laser.

Brief Description of the Drawings

Figure 1 is a block diagram of a prior art CPT-based reference signal generator.

Figure 2 illustrates the optical spectrum generated by the modulated laser of Figure 1.

Figure 3 illustrates a symmetric transmission function.

Figure 4 illustrates the errors that occur when the transmission function is asymmetric.

Figure 5 illustrates some of the energy levels in a typical CPT quantum absorber.

Figure 6 illustrates an asymmetric transmission function and the points used by some of the servo loops of the present invention.

Figure 7 is a block diagram of a frequency standard according to one embodiment of the present invention.

Figure 8 is a block diagram of a frequency standard according to another embodiment of the present invention.

Detailed Description of Preferred Embodiments of the Invention

To simplify the following discussion, it will be assumed that the CPT-generating frequency components are produced by modulating a laser and utilizing two of the side bands as the CPT-generating components. Systems that generate the CPT-generating components by other methods will be discussed in more detail below. The present invention is based on the observation that the asymmetry in the transmission curve can be reduced by utilizing a servo loop to adjust the laser frequency or the laser modulation parameters. In particular, the Rabi frequencies ω_{Ak} and ω_{Bk} for the appropriate values of k can be altered by altering the ratio of the amplitudes of the CPT-generating frequency components in the input light in a manner that reduces the asymmetry in the transmission curve. Alternatively, the center frequency of the laser can be offset to reduce the asymmetry of the transmission curve. In addition, a combination of both servo loops can be utilized.

The manner in which the present invention provides its advantages can be more easily understood with reference to Figure 1, which is a block diagram of a prior art CPT-based reference signal generator 20. Reference signal generator 20 utilizes a laser 22 that is modulated at a frequency determined by a microwave source 27. The modulation frequency will be denoted by ν in the following discussion. The frequency of the laser will be denoted by ν_L. It should be noted that ν_L is also the average of the CPT-generating frequencies in this case. Since laser modulation is well known in the art, a single block 22 representing the modulated laser is shown in Figure 1. It must be emphasized that the electromagnetic source need not be a modulated laser. The present discussion will use a modulated laser to merely simplify the discussion.

The optical spectrum generated by the modulated laser is shown at 30 in Figure 2. The spectrum has a number of frequency components. It is possible to choose any two frequency components as CPT-generating components; for the purposes of this discussion, it will be assumed that the CPT-generating frequency components are the first order side bands as shown at 32 and 33 in Figure 2. In this particular case, $\mu = 2\nu$.

Absorption cell 24 in Figure 1 contains a quantum absorber having two ground states, state A and state B, that are separated by an energy difference corresponding to a frequency difference μ_0, and n excited states, each of which can be connected by separate electromagnetic fields to one or both ground states. One such energy level scheme is shown

in Figure 5. One CPT-generating frequency component induces transitions between state A and one of the excited states as shown at 161 and the other CPT-generating frequency component, induces transitions between state B and that same excited state as shown at 162.

The absorption cell has a minimum in its absorption when the frequency difference of the CPT-generating frequency components 32 and 33, i.e., 2ν, is equal to μ_0 provided the laser frequency, ν_L, is properly set. The intensity of electromagnetic radiation leaving the quantum absorber is sensed by photodetector 28 and controller 29, which sets the value of ν to maximize the transmission of cell 24. Hence, by adjusting the microwave frequency ν to maximize the light transmitted through absorption cell 24, the frequency of microwave source 27 will be equal to a frequency ν_0. In this case, the CPT-generating frequency components 32 and 33 are separated by a frequency difference equal to $2\nu_0$, and $\nu_0 = \mu_0/2$.

The above discussion assumes that the CPT-generating frequency components are the first order sidebands of the modulated laser signal. However, any two frequency components in the modulated light signal can be utilized at the CPT-generating frequency components provided the servo loop can adjust the frequency difference between the two frequency components. For example, standards in which higher order sidebands are utilized can also be constructed. If the N^{th} order side bands are used for the CPT-generating components, the CPT-generating frequency components will be set by the servo loop to a frequency difference of $2N\nu_0$, and the frequency of the microwave source 27 would then be $\nu_0 = \mu_0/2N$. Similarly, the laser frequency and one of the side bands could be utilized, or two side bands of different orders could be utilized.

In the following discussion, ν_0 will be used for the modulation frequency at which the transmission of the CPT-generating frequency components is maximized for the particular choice of frequency components being used. Denote the optical power transmission through the quantum absorber for a microwave modulation frequency of ν by $T_1(\nu)$. As noted above, $T_1(\nu)$ has a maximum for $\nu=\nu_0$. If, for each k, $|\omega_{Ak}|^2 = |\omega_{Bk}|^2$, then $T_1(\nu)$ is a symmetric function about ν_0, i.e., $T_1(\nu)=T_1(2\nu_0-\nu)$. Such a transmission function is shown in Figure 3, which illustrates a transmission function 50. In this case, the servo system can alter the microwave frequency ν to keep the frequency set at ν_0 by measuring the transmission at

microwave frequencies ν-$\Delta\nu$ and ν+$\Delta\nu$. If the current setting ν is equal to ν_0, then $T_1(\nu-\Delta\nu)=T_1(\nu+\Delta\nu)$ as shown at 51 and 52. Suppose ν is less than ν_0, as shown at 59. Then, $T_1(\nu-\Delta\nu)<T_1(\nu+\Delta\nu)$, as shown at 53 and 54. In this case, the controller increases the current value of ν. Similarly, if $\nu>\nu_0$, then $T_1(\nu-\Delta\nu)>T_1(\nu+\Delta\nu)$, and the controller decreases the current value of ν.

Unfortunately, electromagnetic sources may generate CPT-generating frequency components whose associated Rabi frequencies in the quantum absorber do not satisfy the condition, $|\omega_{Ak}|^2 = |\omega_{Bk}|^2$ for each value of k. In such a case, the transmission curve $T_1(\nu)$ is rarely symmetric about ν_0.

An asymmetric transmission curve is shown in Figure 4 at 55. In this example, for increasing ν, the transmission curve decreases more slowly than it increases. Consider the two points shown at 56 and 57. These points lie on different sides of the maximum and have equal transmission values. The average of these two points is a frequency that is greater than ν_0. Hence, if the above-described algorithm is used to determine the location of the maximum, an erroneous result is obtained. The error in frequency is shown at 58. Similar results occur for other types of modulation of the microwave frequency.

The present invention reduces this error either by adjusting the absolute amplitude of each CPT-generating frequency component, or by adjusting the laser frequency ν_L, in a manner that reduces the asymmetry of the transmission curve even when $|\omega_{Ak}|^2 \neq |\omega_{Bk}|^2$ for some value of k. Embodiments that utilize a combination of these two methods can also be constructed.

The present invention uses a servo loop that generates an error signal that is related to some measure of asymmetry in the transmission curve of the quantum absorber as a function of the microwave frequency. The manner in which one embodiment of an asymmetry detector according to the present invention can be more easily understood with reference to Figure 6, which illustrates an asymmetric transmission curve 60. It will be assumed that a microwave frequency servo loop has already adjusted ν such that points 61 and 62 have the same transmission for some predetermined value of $\Delta\nu$. The asymmetry error detector

measures the transmission at two other points, 63 and 64 that correspond to microwave frequencies of $\nu \pm \Delta\nu'$. In one embodiment, the error signal is $T(\nu+\Delta\nu')-T(\nu-\Delta\nu')$; however, any other suitable function of the difference in transmission at the two points can be utilized.

The above-described asymmetry detector assumes that the microwave frequency has been adjusted in a separate servo loop. That servo loop utilizes an error signal related to the difference in transmissions at points 61 and 62, i.e., $T(\nu+\Delta\nu)-T(\nu-\Delta\nu)$, to set the value of ν.

Refer now to Figure 7, which is a block diagram of a frequency standard 100 according to one embodiment of the present invention. For the purposes of this example, it will be assumed that the quantum absorber 102 is irradiated with light from a laser 101. However, other forms of electromagnetic radiation can be utilized as discussed below. The power of the light leaving quantum absorber 102 is measured by a photodetector 103 that generates an output signal that is used by various error detectors and servo loops.

Frequency standard 100 controls the amplitude and frequency of the microwave source that modulates the output of laser 101 via modulation controller 111 that controls the modulation amplitude as discussed above. The frequency of the microwaves is set by voltage-controlled oscillator (VCO) 109 in response to control signals from servo controller 108. The frequency and amplitude of the laser output signal are controlled by optical controller 112 in response to signals from servo controller 108.

Frequency standard 100 utilizes four servo loops to stabilize the frequency of the output signal. The first loop sets ν by changing the output frequency of VCO 109 until points 61 and 62 shown in Figure 6 are equal.

The second and third loops set ν_L. In a conventional CPT-based frequency standard, ν_L is set by a single servo loop 104 that adjusts ν_L such that the transmission curve as a function of ν_L has a minimum. For example, the servo controller causes the laser frequency to be switched back and forth between $\nu_L + \Delta\nu_L$ and $\nu_L - \Delta\nu_L$. The transmission curve is measured at each of these frequencies and an error signal related to the difference in transmission is used to servo ν_L. In a conventional CPT-based frequency standard, this

assures that the laser frequency is set at the point between the transition frequencies to and from states A and B and the common high energy state discussed above. The present invention is based on the observation that the symmetry of the transmission curve as a function of ν can be altered by slightly detuning the laser frequency from this value. The amount of the detuning is determined by asymmetry error detector 105, which generates an error signal related to the difference in transmission that occurs when the microwave source is switched back and forth between $\nu+\Delta\nu'$ and $\nu-\Delta\nu'$ as discussed above. The asymmetry error signal is used to offset the laser frequency error signal generated by the laser frequency error detector 104 to provide the error signal used to servo the laser frequency.

The fourth servo loop adjusts the amplitude of the microwave modulation signal to reduce errors resulting from the AC Stark Shift. The value of ν obtained by the above described three servos depends, in general, on the intensity of the light from laser 101. Hence, fluctuations in the laser intensity lead to fluctuations in the value of ν.

One method for reducing the AC Stark shift operates by introducing additional frequency components (AC-Stark-shift-manipulating frequency components) into the applied electromagnetic field. If the AC-Stark-shift-manipulating frequency components have the correct amplitudes and frequencies relative to the amplitudes of the CPT-generating frequency components discussed above, the AC Stark shift is substantially reduced. In this case, the difference in energy between the two low states utilized for the CPT effect will be insensitive to variations in the total light intensity.

If a phase or frequency modulated laser is used to generate the CPT-generating frequency components, all of the non-CPT generating components act as AC Stark-shift manipulating frequency components. The relative intensities of the AC-Stark-shift-manipulating frequency components are controlled by adjusting the amplitude of the microwave signal applied to modulate the laser. The modulation amplitude can be adjusted with a servo loop that utilizes an error signal obtained by switching the laser intensity back and forth between two slightly different intensities and measuring the difference in ν obtained at each of these intensities. The difference in the measured value of ν is then used to generate

an error signal that is used by servo controller 108 to adjust the amplitude of the modulation signal that is applied to laser 101.

Refer now to Figure 8, which is a block diagram of an embodiment of a frequency standard 200 according to another embodiment of the present invention. To simplify the following discussion, those elements of frequency standard 200 that operate in a manner analogous to elements discussed above with reference to Figure 7 have been given the same numeric designations and will not be discussed in detail here.

Frequency standard 200 alters the amplitudes of the two CPT-generating components to reduce the asymmetry in the transmission function discussed above. The relative amplitudes of the CPT-generating components can be altered by modulating both the amplitude and phase of the laser output. Specifically, the relative amplitudes of the CPT-generating components can be altered by adjusting the depth and/or phase of the amplitude modulation relative to those for the phase modulation. As noted above, the depth of the phase modulation is also used to alter the ratios of the CPT-generating components and the other side bands that are utilized to reduce errors due to the AC Stark Shift discussed above. In frequency standard 200, modulation controller 211 has inputs for controlling the modulation of both the phase and amplitude of the laser. One of these is used to correct for the AC Stark Shift and the other is used to reduce the asymmetry of the transmission curve. The error signal generated by asymmetry error detector 205 is used by servo controller 208 to servo the amplitude modulation, and the error signal generated by AC Stark Shift detector 206 is used to servo the phase modulation.

Since adjusting the amplitudes of the CPT-generating components equalizes the absolute value of the relevant Rabi frequencies, the degree of correction obtained in the second embodiment is, in principle, greater than that obtained by detuning the laser frequency. However, the dynamic range available in the phase or amplitude modulations may not be sufficient to completely equalize the Rabi frequencies in some cases. In such cases, the two strategies can be combined by using the detuning of the laser frequency to reduce the asymmetry to a level that is within the range of the Rabi frequency equalization mechanism.

The above-described embodiments of the present invention utilize a modulated laser as the source of electromagnetic radiation to induce CPT in the quantum absorber. However, other suitable electromagnetic radiation sources can be utilized. For example, a light source can be constructed by phase locking two lasers that differ in frequency by an amount that can be controlled by a servo. In addition, the teachings of the present invention can be applied to electromagnetic radiation sources that are outside the optical range. It should also be noted that the frequency at which the EM source is modulated can be outside the microwave range. Such a case will occur for quantum absorbers in which the low-energy states are separated by frequencies outside of the microwave range.

In the above-described embodiments, the CPT-generating frequency components were two side bands in the modulated laser spectrum. However, as pointed out above, any two frequency components in the spectrum can be utilized. Hence, in the general case, ν_L is the average of the two CPT-generating components, and the detuning servo is applied to the controller that determines this average.

Similarly, if two phase-locked lasers are utilized, the detuning servo sets the average frequency of the two lasers. For example, the frequency of one of the lasers can be altered, and the phase-locking circuitry will then move the other laser's frequency to a frequency that maintains the difference in frequency specified by the servo that sets ν.

The above embodiments of the present invention have been directed to frequency standards in which the goal is to produce a standard signal whose frequency is relatively insensitive to variations in environmental conditions. However, the present invention can also be utilized to construct a sensor that measures some physical quantity such as magnetic field strength. Consider a quantum absorber in which the CPT is based on two low energy states having an energy difference that depends on an external magnetic field that is applied to the quantum absorber. By measuring the modulation frequency at which the CPT is maximized, the strength of the external magnetic field can be deduced.

For example, a magnetic field strength measuring apparatus can be constructed using transitions between states of ^{87}Rb. The energy levels in the ground states of ^{87}Rb shift in response to an external magnetic field that is applied to the atom. If two ground states are

chosen in which the energy difference of the ground states is a function of the applied magnetic field, the frequency of the output signal, which is determined by the frequency difference between the two CPT-generating frequency components, can be used to measure the magnetic field. Similar sensors can be constructed to measure electric field strength or other environmental variables by choosing the suitable energy states in a suitable quantum absorber for CPT generation.

The quantum absorber discussed above can be any material that exhibits the CPT effect. For example, alkali metals such as lithium, sodium, potassium, rubidium, and cesium can also be utilized. In addition, suitable ions, molecules, or doped solid materials can be utilized. In particular, ions that are isotopes of Be^+, Mg^+, Ca^+, Sr^+, Ba^+, Zn^+, Cd^+, Hg^+, and Yb^+ can be utilized.

Various modifications to the present invention will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Accordingly, the present invention is to be limited solely by the scope of the following claims.